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A Novel Method of Minimizing Power Consumption for Existing Chiller Plant

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Abstract

Chiller consumes a significant power ratio in HVAC system. In order to minimize the power consumption of chiller, many efforts have been made on load predictions and optimal control strategies. The performance of chiller (e.g., COP) and dedicated devices (e.g., operation variables) play very important roles in chiller power consumption. However, it is difficult to find proper model to predict accurate chiller COP chiller in practice. Moreover, how the operating variables of the chiller system affects the over power consumption need to be identified. This paper therefore aims to find out a simple and accurate COP prediction model for chiller and investigates the optimal values of operating variables related to the chiller system. By com-paring kinds of models (e.g., SL, BQ, MP, GNU, QHP and BP-ANN), BP-ANN is considered as the proper model in predicting COP of chiller accurately. By adopting GA-based operating variables identification, optimal values of the variables can be found in specified ranges as well. This study evaluates the performance of different COP prediction models by using actual operation data of chiller plant in a commercial building. Furthermore, optimal settings for operating variables have also been identified in resulting of minimum power consumption of chiller plant.

Keywords: Chiller plant; Power consumption; Coefficient of performance; Genetic algorithm; Artificial neural network; Variable optimization; HVAC system

1. Introduction

With the continuous improvement of living quality and demand for high quality of indoor environment, the central air-conditioning system has been widely used in different types of buildings. A significant amount of energy

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has been wasted due to the lack of effective controls. This paper proposes a novel method of minimizing the power consumption for HVAC system in DAS building. The least-squares regression method and the back propagation artificial neural network (BP-ANN) are employed to find out the characteristics of the HVAC sys-tem and to minimize their power consumptions. By considering main variables as model inputs, six models are used to estimate their accuracies in predicting the coefficient of performance (COP) of chiller. By conducting the data processing and training among the models, the BP-ANN model was found having the highest accuracy. The BP-ANN is therefore employed for estimating and optimizing power consumption of chillers, chilled water pumps and cooling water pumps. In this study, genetic algorithm (GA) is employed to process the optimization for the real data of HVAC system in DAS building. It is worth noting that average energy saving can be 23.32% in summer, 9.06% in winter, and 10.85% in transitional seasons respectively.

Nomenclature

$T_{ch,sup}$	chilled water supply temperature
$T_{ch,rtn}$	chilled water return temperature
M_{ch}	chilled water flow rate
$P_{ch,p}$	power consumption of chilled water pump
$F_{ch,p}$	frequency of chilled water pump
COP	coefficient of performance of chiller
$P_{chiller}$	power consumption of chiller
$T_{cl,sup}$	cooling water supply temperature
$T_{cl,rtn}$	cooling water return temperature
M_{cl}	cooling water flow rate
$P_{cl,p}$	power consumption of cooling water pump
$f_{cl,p}$	frequency of cooling water pump
P_{fan}	power consumption of cooling tower fan
f_{fan}	frequency of cooling tower fan
T_{wb}	outdoor wet bulb temperature
T_{out}	outdoor dry bulb temperature
RH	outdoor relative humidity
Q	cooling capacity

1.1. HVAC System Profile

DAS INTELLITECH building is a six-floor building with built-up area 18,000m2. HVAC system of DAS building consists of three screw type chillers, four chilled water pumps (note: with VSD and one pump for backup), four cooling water pumps (note: with VSD and one pump for backup) and three cooling towers. Details of HVAC components are listed in Table 1.

Table 1. Technical details of devices in HVAC system.

Item	Rated power	Number
Chiller	Rated cooling capacity: 1,055 kW, Rated power: 203 kW	3
Chilled water pump	22 kW	4
Cooling water pump	30 kW	4
Cooling tower with two fans	2×4 kW	3

The HVAC system is monitored and controlled by an automatic energy saving management and control software named EMC007. All the history and real time operation data of HVAC system can be collected by this software platform. Moreover, the control strategies (e.g., global group-control strategy) are also built in the software platform and the basic control principles (e.g., local interlock start/stop strategy) are written in the PLC (programmable logic controller) module as well.

The distribution of different component power consumption of HVAC system in year 2015 is: chillers took 79%, the other devices took more than 20% of total power consumption, where the ratios of chilled water pumps and cooling pumps are 8% and 9% respectively. While the cooling towers only consumed 4%. As there are many factors affecting efficiency/performance of HVAC components in the chiller plant and complex coupling relationships among them. This paper aims to find out a proper method/process to optimize the operation of HVAC system operation and minimize the power consumption of HVAC system.

2. Methods

2.1. Experiment Settings

As mentioned above, the operation variables and parameters are highly coupling and inter-connected. The performance of the whole HVAC system can therefore be quite different if there are any slight changes of the variables and parameters. Power consumption models should be established to simulate the entire HVAC system. Although the COP of chiller can be obtained by calculating the chiller power consumption and supplied cooling capacity. Moreover, the power consumption models of the motors (e.g., pumps and cooling tower fans) can be also easily obtained by collecting frequency information from VFD (variable frequency drives). However, in some cases, even though the performance of chiller is quite high while the other components are not at their efficient operation range. This usually results a high power consumption of HVAC system. The proposed method therefore aims to compromise the power consumption of chiller and that of the rest electrical devices in chiller plant to make sure the lowest power consumption of the HVAC systems during the operation period.

2.2. Data Processing

The data acquisition frequency of collecting and storing operation data of the HVAC systems is ten minutes. In this study, hourly data in year 2015 (i.e., 8,760 sets of data) of the variables and parameters (e.g., chilled water supply temperature, cooling water flow rate etc.,) are used to conduct data process and analysis.

2.3. Modeling

Generally, a mathematical model is a description of a system using mathematical concepts and language (Wikipedia 2015). In this study, the relationships between different variables in the HVAC system can be theoretically expressed in by a white model. However, kinds of situations, such as the erosion of devices, the efficiency of electrical devices and uncertain internal and external factors etc., have to be considered in practice. Moreover, all the physical expressions of these situations may be immeasurable or unobtainable. The black box models are therefore considered as the suitable approach for the HVAC system simulation by considering data requirements, computing time and accuracy.

On premise of a modeling, prediction accuracy is a very important indicator to examine the predicting capabilities. The coefficient of variation of root-mean-square error (note: abbreviated as CV in following content) is used to indicate model prediction accuracy. CV is defined by Equation (1).

$$CV = \frac{RMSE}{\left|\left(\sum_{i=1}^{n} y_i\right) / n\right|} \tag{1}$$

Where, RMSE is the root-mean-square error of a model identified from data and is defined by Equation (2).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \tag{2}$$

Where, y_i is the measured data, $\hat{y}_i$ is the predicted data, n is the number of data sets. Another indicator of predicted accuracy is the confidence interval of 95% (note: abbreviated as CI in following content), which is especially useful for detecting shifts in the process mean or variability using statistical process control charts (Swider 2003).

BP-ANN Model (MacKay and David 2003) is employed to compare the prediction effect with those of the SL Model (Swider 2003), BQ Model (Swider 2003),MP Model (DOE 1980) ,GNU Model (Ng et al. 1996) (Gordon and Ng 2000) and QHP Model. Results show that BP-ANN gets the best prediction accuracy, as show in Fig. 1.

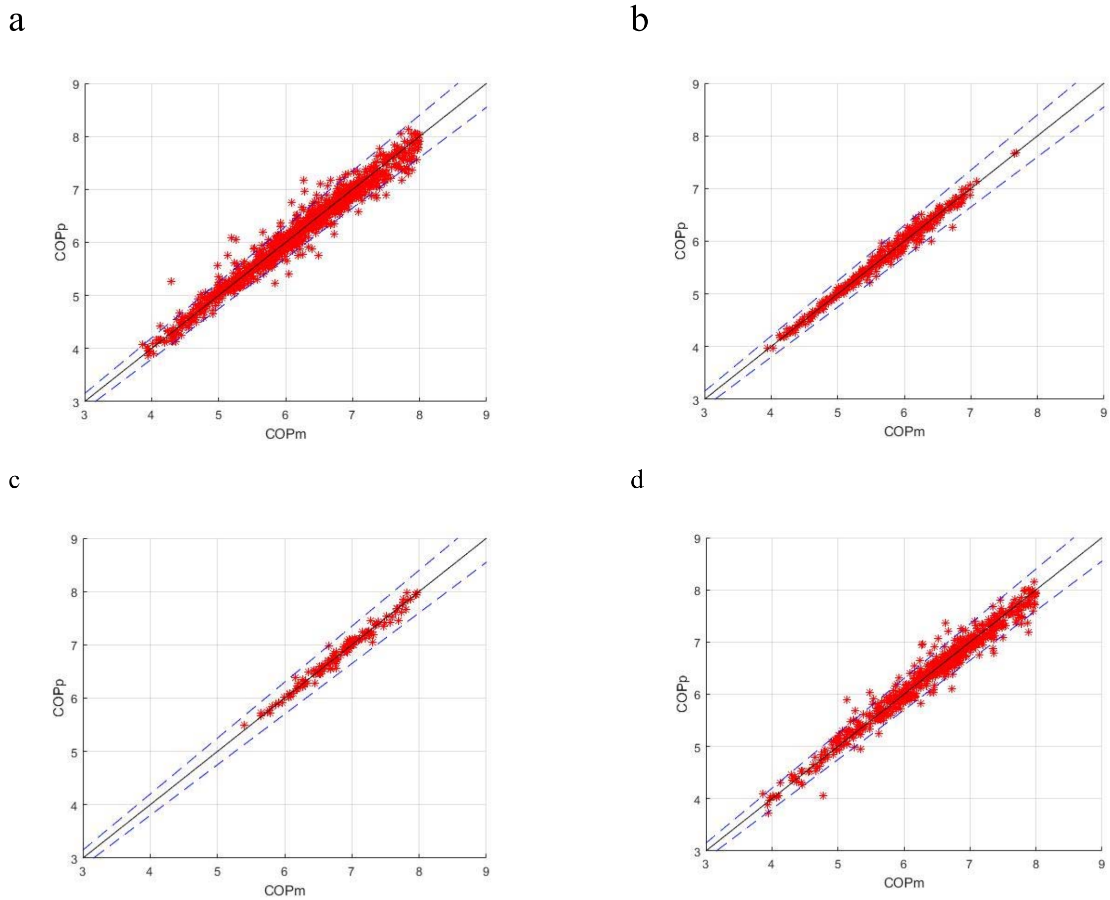

Fig. 1. Validation of BP-ANN model for entire period (a), summer (b), winter (c) and transitional seasons (d).

3. Results

By conducting the validations of BP-ANN model and the other models for operation data from entire period, summer, winter and transitional seasons, the prediction results of BP-ANN model are obviously much better than those of the other black box models. Especially for the validation in winter, 100% of the prediction results are fallen in the confidence interval of 95% (i.e., CI). By comparing with the other models, these four figures have smaller CV and have more percentage of prediction results falling in the confidence interval of 95%. Comparison details are listed in the Table 2.

Table 2. CV and CI of different models.

Item	SL	Summer	Winter	Transitional seasons	BQ	Summer	Winter	Transitional seasons
CV	0.1287	0.1147	0.0839	0.1337	0.0584	0.0463	0.0557	0.0626
CI	21.79%	27.89%	43.80%	11.87%	64.11%	70.79%	69.06%	65.71%
Item	MP	Summer	Winter	Transitional seasons	GNU	Summer	Winter	Transitional seasons
CV	0.0571	0.0544	0.0308	0.0551	0.1039	0.091	0.0596	0.0791
CI	64.60%	67.02%	94.24%	67.57%	32.48%	41.73%	69.50%	53.80%
Item	QHP	Summer	Winter	Transitional seasons	BP-ANN	Summer	Winter	Transitional seasons
CV	0.0561	0.0482	0.0559	0.0675	**0.0267**	**0.0156**	**0.0117**	**0.0258**
CI	70.16%	79.17%	71.22%	62.31%	**94.00%**	**99.22%**	**100%**	**94.08%**

Based on above comparisons, the BP-ANN model is therefore chosen as the suitable model for predicting and optimizing the power consumption of HVAC system in DAS building. The process of prediction and optimization of power consumption is presented as following steps:

Step 1: The BP-ANN model is employed to estimate the relationship between the chiller COP and the other seven variables, as shown in Equation (3). According to the definition of COP shown in Equation (4), the power demand of chiller can be represented by Equation (5).

$$COP = f_o\left(M_{ch}, T_{ch,\sup}, T_{ch,rtn}, M_{cl}, T_{cl,\sup}, T_{cl,rtn}, Q\right) \tag{3}$$

$$P_{chiller} = \frac{Q}{COP} \tag{4}$$

$$P_{chiller} = f_1\left(M_{ch}, T_{ch,\sup}, T_{ch,rtn}, M_{cl}, T_{cl,\sup}, T_{cl,rtn}, Q\right) \tag{5}$$

Step 2: BP-ANN model is also employed to predict the other three main electrical devices (i.e., chilled water pumps, cooling water pumps and cool towers) in the HVAC system, as shown in Equation (6)-(8).

$$P_{ch,p} = f_2\left(M_{ch}\right) \tag{6}$$

$$P_{cl,p} = f_3\left(M_{cl}\right) \tag{7}$$

$$P_{\text{fan}} = f_4\left(M_{cl}, T_{out}, RH\right) \tag{8}$$

It is worth noticing that the power demand of cooling towers is considered to be rigid in this study, because the frequencies of cooling tower fans were set to constant during 2015.

Step 3: The total power demand of the whole HVAC system can then be expressed by seven variables, as shown in Equation (9)-(10).

$$
\begin{aligned}
P_{tot} &= P_{chiller} + P_{ch,p} + P_{cl,p} \\
&= f_1\left(M_{ch}, T_{ch,\sup}, T_{ch,rtn}, M_{cl}, T_{cl,\sup}, T_{cl,rtn}, Q\right) + f_2\left(M_{ch}\right) + f_3\left(M_{cl}\right)
\end{aligned} \tag{9}
$$

$$
P_{tot} = f_4\left(M_{ch}, T_{ch,\sup}, T_{ch,rtn}, M_{cl}, T_{cl,\sup}, T_{cl,rtn}, Q\right) \tag{10}
$$

According to Equation (10), once the variables are identified, the total power demand can then be predicted accordingly. The prediction can be finished by searching the minimization of the system power demand by genetic algorithm (GA).

4. Discussion

4.1. Minimization of Power Consumption in HVAC System

There are many advantages of GA using for multi-objective engineering optimization com-pared with traditional optimization algorithms, for instance, the ability of dealing with complex problems. Table 3 lists the searching ranges for the main operation variables according to the minimum and maximum values of real data respectively. Table 4 shows the details of the main operation variables after the optimization in power consumption of chiller plant.

Table 3. The searching range for the main operation variables in chiller plant

Parameters	Symbol	Searching Range	Unit
Chilled water supply temperature	$T_{ch,sup}$	[7,13]	℃
Chilled water return temperature	$T_{ch,rtn}$	$(T_{ch,rtn} - T_{ch,sup}) \in [5, 7]$	℃
Chilled water flow rate	M_{ch}	$M_{cl} = \dfrac{Q}{4.2 \times 10^6 (T_{ch,rtn} - T_{ch,\sup})}$	$m^3 \cdot s^{-1}$
Cooling water supply temperature	$T_{cl,sup}$	[30, 35]	℃
Cooling water return temperature	$T_{cl,rtn}$	$(T_{cl,rtn} - T_{cl,sup}) \in [0, 7]$	℃
Cooling water flow rate	M_{cl}	[0,0.2]	$m^3 \cdot s^{-1}$

Table 4. The operation variables after the optimization in power consumption of chiller plant

Time	Q[kW]	$M_{ch}[m^3 \cdot s^{-1}]$	$T_{ch,sup}$[℃]	$T_{ch,rtn}$[℃]	$M_{cl}[m^3 \cdot s^{-1}]$	$T_{cl,sup}$[℃]	$T_{cl,rtn}$[℃]
09:00	900.11	0.037	10.66	16.52	0.088	34.33	39.71
10:00	595.77	0.023	10.11	16.40	0.088	30.41	36.62
11:00	548.01	0.020	9.88	16.39	0.070	32.12	37.27
12:00	518.75	0.018	10.26	17.19	0.077	32.24	38.98
13:00	527.66	0.019	10.42	17.05	0.086	31.66	35.82
14:00	516.48	0.018	10.63	17.32	0.082	33.54	38.86
15:00	493.38	0.019	10.26	16.51	0.089	31.78	37.50
16:00	482.08	0.017	10.07	16.64	0.085	33.12	37.54
17:00	478.37	0.018	10.70	16.93	0.085	32.97	37.34

Fig. 2 shows that the power consumption of the whole HVAC system has a significant reduction in a typical summer day by adopting GA optimization. Compared with the reference case (i.e., without GA optimization in power consumption), the more power the system consumed, the more power saving potential it has. Especially when there are more than one pump (e.g., chilled water pumps or cooling water pumps) are running, the system gets more energy saving potentials in part load operation. Fig. 3 shows the energy saving rate for the typical summer day with a quite good average energy saving rate 23.32%.

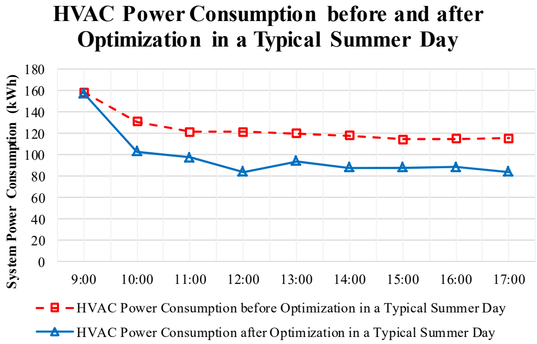

Fig. 2. HVAC Power Consumption before and after Optimization in a Typical Summer Day (18th.July.2015)

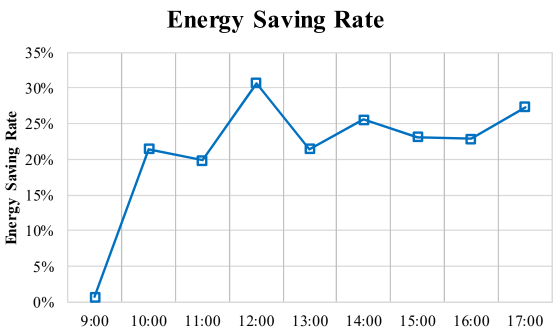

Fig. 3. Energy saving rate in a typical summer day (18th.July.2015) by adopting BP-ANN Optimization

In reference case, the power consumption of chilled water pumps takes 7% (75.46 kWh) and the chiller power consumption takes 84% (930.63 kWh). In optimal case, the power consumption of chilled water pumps takes 8% (67.01 kWh) and the chiller power consumption takes 83% (699.90 kWh). Table 5 lists the details of the comparison

Table 5. Comparison of power consumption in reference case and optimal case

Item	Before Optimization	After Optimization	Energy Saving Rate
Chiller	930.63 kWh	699.95 kWh	24.79%
Chilled water pumps	75.46 kWh	67.01 kWh	11.20%
Cooling water pumps	109.92 kWh	117.84 kWh	-7.21%
Total power consumption	1116.01 kWh	884.80 kWh	20.72%

4.2. Energy Saving in Winter and Transitional Seasons

For winter and transitional seasons, the GA is also adopted in BP-ANN model and succeeds in decreasing the total power consumption of HVAC system. The power consumption reductions of the HVAC system are respectively 9.06% and 10.85% for winter and transitional sea-sons. The power consumption reductions of the HVAC system in winter and transitional sea-sons are not as high as those in summer. It is because the HVAC system operates at part load in most time of these seasons. Moreover, the HVAC system supplies the cooling capacity mainly for external dehumidification instead of internal cooling load in transitional seasons.

5. Conclusions

In this paper, six black box models, (i.e., SL, BQ, MP, GNU, QHP and BP-ANN) were employed to validation the prediction accuracy for the power consumption of the HVAC system. BP-ANN model was found to be quite suitable for estimating the power consumption characteristics in HVAC system thanks to its high accuracy in prediction (in the study, the accuracy is as high as 94% in the confidential interval of 95% and the root-mean-square error is quite small). Genetic algorithm was also employed for optimizing and minimizing the total power consumption of the HVAC system. The simulation results show that 23.32% energy saving in summer, 9.06% energy saving in winter and 10.85% energy saving in transitional seasons.

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